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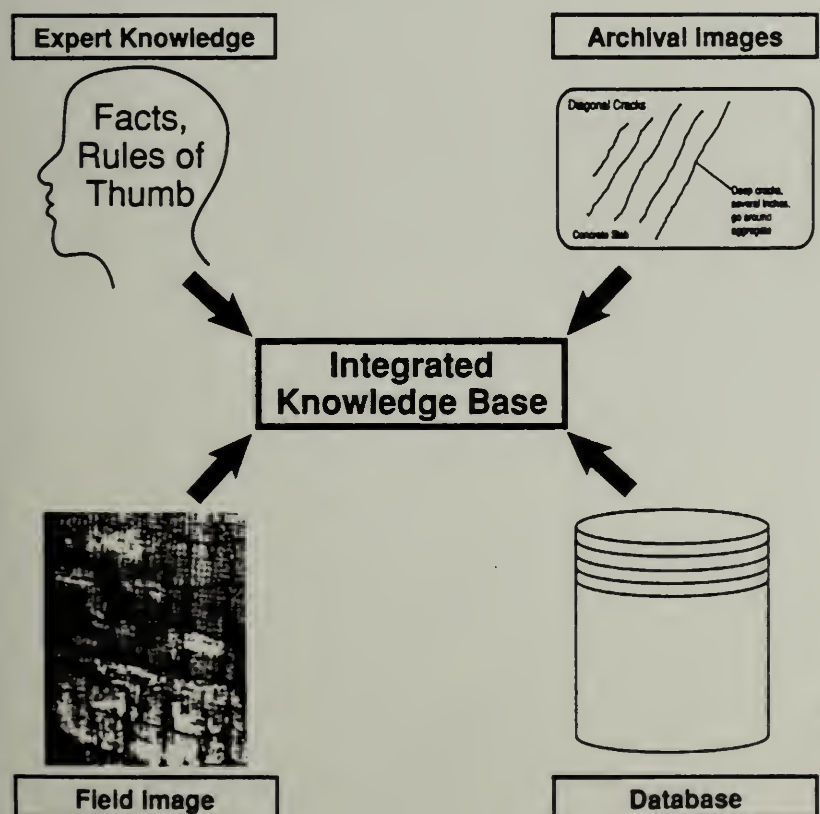

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ABSTRACT

An expert system has been developed for identifying the probable causes of cracks in concrete based on their shape and pattern, density and location. The system uses three forms of knowledge; 1) facts & rules of thumb, 2) databases, and 3) digital imaging capabilities. Knowledge contained in the system is obtained from experts in the field, photographs taken of actual concrete failures, and the classification of the failures into a database format. A PC based expert system shell and computer programs written specifically for the integration and use of the different forms of knowledge were used to implement the expert system. This paper discusses the acquisition of the three forms of knowledge, their representation in the expert system environment, and extensions developed to process information and enhance the user's interface. The potential for the use of speech recognition for recording conditions at field sites, and storage of large volumes of information using optical disk technology are discussed.

Keywords: concrete cracking, database, diagnostics, expert system, image processing, knowledge acquisition

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1. INTRODUCTION

Expert systems are potentially powerful tools for the building industry [1]. The use of these systems will aid designers, facility's managers, inspectors and educators design and construct better buildings and structures, making maintenance management decisions for the repair of structures and assuring that buildings meet accepted guidelines, practices and building code requirements for safety and performance. In addition, the knowledge of high-level experts will be preserved in these systems. Examples of early expert systems developed for the building industry include; WATERPEN, WINDLOADER, TIMBER EXPERT- expert systems for building construction [2]; RAILS - an expert system for railroad construction [3]; DURCON - an expert system for designing durable concrete [4,5].

The acceptance of expert system technology will depend largely on the availability and maturity of tools (shell programs and languages) for developing the systems. In the past three years for example, the number and quality of expert system shells for use on desktop microcomputers has grown rapidly. Central processor speed, cost of computer equipment, and wide-spread use of these systems for a multitude of applications has created an attractive platform for expert systems development. Yet to be accomplished, however, is the capability of development tools to relieve the domain expert/developer's need to become a computer expert.

In this paper, an expert system for diagnosing the causes of concrete cracking is described. The emphasis is on the methods used to integrate knowledge and to enhance the user interface through explanatory feedback. The implementation of computer imaging and voice systems to aid in the interpretation of expert system recommendations and conclusions is also presented.

2. EXPERT SYSTEMS AND CONDITION ASSESSMENT

Condition assessment of buildings includes the determination of percent area of deterioration of painted surfaces (e.g. chipping, peeling) and diagnosing the causes of failures in materials, such as concrete (e.g. cracks, deterioration) and roofing materials. Current practice in assessing the condition is to rely on human observations made by inspectors. These methods are often subjective and vary between individuals. Unlike human observations, expert systems are consistent, and when combined with automated techniques such as image processing, produce quantitative results which can be validated by acceptable test methods.

Another advantage of expert systems for condition assessment is the ability to measure the rate of deterioration of structures

by comparing observations taken at different time periods. This information is important to facility's managers who must make decisions concerning maintenance. As funding allocations for building maintenance are reduced, the ability to make accurate estimates on costs and schedules becomes more important.

3. CRACKS EXPERT SYSTEM KNOWLEDGE BASE

Different forms of knowledge are needed to make expert decisions about the condition of a structure. These often are represented in the form of:

- o facts, expert opinion, guidelines, rules of thumb
- o descriptive information (building characteristics)
- o visual information (photographs, drawings)

The CRACKS expert system makes use of the above three forms of knowledge to make conclusions concerning the probable cause of non-structural cracks in concrete. An example session from CRACKS is presented in Figure 1.

Facts, expert opinion and rules of thumb were obtained from experts. For the most part, it was obtained from narrative text prepared by experts to describe the relevant information necessary to make a judgement about the cause of concrete cracking. Interviews were conducted with experts to obtain information on correct diagnostic procedures. From these interviews, a knowledge hierarchy was developed. The process of developing a hierarchy contributed to the development of the expert system by providing a graphical representation. This was then translated into the expert system shells' production rule language. A portion of the CRACKS knowledge tree is presented in Figure 2.

Descriptive information about the structure or structural element such as its type, size or type of materials used in construction is stored in the database component of the knowledge base. This information is obtained from the building owner or from field inspections and tests. Each archival image stored in the CRACKS expert system is represented by a corresponding database record which describes it. The process used to describe the image is illustrated in Figure 3. The database schema is shown in Figure 4. Once an image is described and stored in the database, it is used in the expert system for making conclusions about the cause of concrete cracking. Fields contained in the database such as "type_problem" and "element" are used to locate images which relate to a specific failure mode.

The CRACKS imagebase consists of digitized photographs and drawings stored in the computer. This information was obtained from two sources; 1) field investigations in which the cause of

cracking was determined, such as plastic shrinkage or alkali-aggregate reactions; and 2) from technical reports such as The Concrete Society Report on Concrete Cracking [6]. Images are used within the expert system for the visual display of cracking problems. This visual display assists the user in determining the type of cracking which relates to the specific problem by allowing the user to view many types of cracks. Figures 5 and 6 are examples of images which are stored in the CRACKS imagebase.

4. CRITERIA FOR SELECTING EXPERT SYSTEM DEVELOPMENT TOOLS

Work at the National Institute of Standards and Technology (NIST) in developing expert systems has focused primarily on the expert system domain application instead of developing tools for expert systems. These include expert systems for concrete durability [4,5,7], maintenance of painted structures and concrete cracking. The criterion for selecting the expert system tools currently in use is:

- o knowledge representation (rule-based, frame based)
- o shell environment for rapid implementation and maintenance
- o extensive interface capabilities for external data and user developed programs
- o available for personal computer environment
- o quick interactive response to user

Several expert systems shells were investigated and tested. These included, Insight[1], M.1[2], and EXSYS[3]. In 1986, when expert system tools were being evaluated, there were 30+ shell programs available for personal computers. Most of these programs were developed for particular market applications and had limited capabilities (such as external calls) or were too expensive. The evaluation resulted in the selection of the Insight product. The speed of the expert system shell, the editing and debug facilities available for developing expert systems was adequate for the intended applications. At that time, it lacked the external interfaces for passing information between the expert system and user programs. This was later improved and Level 5

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[1]Insight formerly a product of Level 5 Research is now called Level 5 PC, a product of Information Builders [8].

[2]M.1 is a product of Teknowledge[9].

[3]Exsys is a product of EXSYS, Inc. [10].

PC[4] now hosts one of the most extensive interfaces available for personal computer-based expert system development tools.

5. ADAPTING THE EXPERT SYSTEM SHELL TO THE USER ENVIRONMENT

In the development of expert systems, it is crucial that the specific needs of the user are met. In selecting an expert system shell program, it became obvious that some requirements could not be met with a commercial product. Therefore, it was necessary to extend the capabilities of the expert system tool by developing special features that improved the user interface and to provide access to external capabilities such as computer image processing. The computer programs developed to enhance the CRACKS expert system are listed in Table 1. Some user interface facilities do exist in the Level 5 shell program. These include; 1) the ability to give the user explanations of why a question is being asked and, 2) display information on the computer screen to provide background information, 3) display a question in a precise format.

5.1 Enhanced User Interface

For the CRACKS expert system, special facilities were developed. The extended facilities provided by CRACKS are:

- a chronology of the knowledge base development and changes
- storage of information during expert system execution to provide background information for conclusions
- a printed record of the conclusions and line of reasoning in graphic form

The development of these extended capabilites for CRACKS involved writing computer programs in C and PASCAL programming languages. The programs are "activated" at precise times during the firing of the expert system rules.

5.2 Interfacing Specialized Capabilities

Visual information such as photographs and drawings enhance the interpretation of results and can often better describe failure modes for materials and structures. Computer image processing is one way of interfacing this form of information to the user. In addition, computer image processing can be used to

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[4]This and other trade names and company products are identified to specify adequately the work presented. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology.

automate the process of analyzing a view of a structure and provide a consistent and accurate method of obtaining quantitative statistical information. Preliminary research indicates that statistical results obtained from image processing can be used in the firing of expert system rules. Computer programs have been developed for CRACKS to capture, enhance and display computer images during a session. As additional computer image processing capabilities are developed, they will be integrated into the system.

6. EXPERT SYSTEM DESIGN

The design of the CRACKS expert system promotes the use of several forms of knowledge and the latest computer hardware technology. The knowledge forms have been described earlier in this paper. This section will describe the methods of interfacing the knowledge and the hardware and software configuration. Figure 7 shows a configuration of the CRACKS expert system.

6.1 Method of Integrating Knowledge Forms

The design of the CRACKS mechanism for integrating knowledge permits the communication of information between the expert system inference engine rules, database files and stored images through the Level 5 "activate" feature and user developed programs. An example of the use of this mechanism is described in the following scenario.

Given that a cracking problem exists which is caused by plastic shrinkage, and the expert system needs to search all examples of images which relate to this type of problem. An expert system rule would be fired which uses the Level 5 "locate" function to search the database field "type_problem" which could contain a value identifying the problem as plastic shrinkage. If a record is located containing the type problem, then the value of that record is placed in the context. The Level 5 "activate" function is then called to execute the user developed program which displays the image on the image screen. This process continues until an end of file condition is detected on the database file. Figure 8 shows an example of the expert system knowledge base linkages.

6.2 Computer Hardware and Software Capabilities

A major consideration in selecting computer hardware and software for the CRACKS expert system was the desirability of providing a low-cost computer environment for the end user. For this reason, a microcomputer system was chosen, and much of the computer software was purchased commercially. Since many field sites already have computer systems similar to this type, the

typical user is familiar with their use.

Specifying the computer hardware and software for the expert system involved identifying the most important features. These were:

- o fast central processing unit
- o fast transfer of information within the computer system (high-speed data bus)
- o ability to store large amounts of information in the knowledge base (database, images)
- o available image processing hardware and software
- o programming language and libraries meet the interface requirements of the expert system shell program

The computer hardware and software described in Tables 2 and 3 met all of the requirements. In addition, it provided a platform for future enhancements and expansion of the expert system to include an expanded rule base for a more complex application domain, and the ability to store large volumes of information.

7. EXPERT SYSTEM SHELL EXTENSIONS

7.1 COMPUTER IMAGE PROCESSING

7.1.1 Image Capture and Display

Computer image processing involves the acquisition, processing, storage and retrieval of photographs and drawings. A video camera is used to digitize the source drawing or photograph of a concrete crack and store it in the computer. A computer hardware board called a frame grabber provides the analog-digital conversion of the image and stores the information in a frame buffer in units called pixels. At this point, the digitized image can be enhanced, processed or stored on the computer's magnetic disk. Figure 9 shows the steps needed to acquire and store a photograph in the CRACKS expert system. Once the image is stored on disk and a database record is established to describe the image, it is available for use by the expert system's inference engine.

Two categories of computer software are needed to accomplish the acquisition and storage. The first involves the use of a library of image processing programs to perform the imaging functions. This software is written specifically to operate with the image processing hardware board. Table 4 lists the capabilities of the imaging software used for CRACKS. The second level of computer software is the application program. It defines the functions needed to perform the imaging operation by calling the appropriate sub-programs from the imaging library.

The following example demonstrates the calls to the image processing sub-programs library needed to initialize the imaging hardware and retrieve an image from disk.

```
    { setup image board  }
         sethdw(registerbase,memorybase,bwflag};
         initialize;
         sclear{128,wait};

    { retrieve image from disk }
         if {readim(0,0,511,511,filename,comline) <0) then
              write('error reading image file  ');
```

This example was written in the PASCAL programming language and is an excerpt from the program used by the CRACKS expert system. The user would see the image display screen clear and the image identified in the parameter "filename" in the call to sub-program "readim" would be displayed.

Currently, only capture and display facilities are used by the CRACKS expert system. Image enhancement and image processing functions can also be performed using a pointing device such as a mouse or joystick. These operations are not available in CRACKS and must be performed separately. They will be incorporated in a later version. Research on the feasibility and application of image processing with CRACKS is described in the next section.

7.1.2 Image Processing of Cracks

Within the knowledge tree of CRACKS, several questions are asked concerning the geometry of the unknown crack patterns (such as single or multiple cracks, random or parallel orientation, and diameter of the overall crack pattern). Since CRACKS has been designed to incorporate imaging capabilities, it may be possible for the computer to automatically evaluate (via image analysis) the geometry of the crack patterns, thus reducing the knowledge required from the expert system user. To successfully implement this automated analysis, two issues must be addressed. The first concerns the quality of the photographs of cracks obtainable by field personnel. If the crack patterns cannot be isolated from their background, quantitative evaluation of their geometry will not be possible. Fortunately, research in this area for other building materials such as coatings [11] has shown that if the human observer can identify the defects in the photograph, generally, software can be developed so that the computer can also execute this task.

The second issue concerns what statistics can best characterize (distinguish) the various possible crack patterns. Based on the current knowledge tree for CRACKS, three likely candidates are the number of cracks and orientation and the expanse of individual cracks. Once cracks have been isolated,

producing a binary image of black cracks on a white background (see Figure 10), and counting the number of individual cracks is an easy task for the image processing computer. As each individual crack is found, a number of features can be characterized (area, perimeter, etc.) can be determined. Based on the moments of individual crack areas, orientation and eccentricity (a measure of the expanse of a crack) may be determined using standard formulas [12]. These values would then be utilized by the expert system to assist in determining the probable cause of the observed cracking. For example, if the system determines that a few, parallel (similar orientations) cracks are present, probable causes would include, rebar corrosion or settlement before hardening. Finally, these statistics could be continuously added to the database to be accessed by the expert system, so that the knowledge base could become more refined as time progresses and thus, the system would actually improve its performance in terms of correct automatic identification of crack patterns utilizing image analysis of crack pattern geometry.

7.1.3 Explanatory Capabilities

The importance of an enhanced user interface was discussed previously in this paper. The computer programs which were written to accomplish this are described in Table 1. Specifically, the functions provided by these programs are to:

- o manage the display text screen (initialize, clear)
- o provide file management for text files generated during a CRACKS session
- o display conclusions made by the expert system
- o provide printed reports of conclusions and line of reasoning

7.2 FUTURE ENHANCEMENTS

7.2.1 Automating the Knowledge Acquisition and User Input Process

The current method of obtaining user input and knowledge for the expert system is to request responses from the user during a session and to catalogue the characteristics of a photograph or drawing in the expert system database and imagebase. A more reliable and consistent way of obtaining this information could be to develop automated methods of acquiring field information such as using voice recorded observations about the condition of a structure and play this back to the computer. This method is currently being evaluated at NIST. The intent is to provide a field inspector with guidelines on how to perform the field inspection, how to obtain the most desireable photograph of the cracking and how to record this information so that the expert

system can use it during the session. It is also possible to have the computer analyze the photograph (image) and reduce the number of rules required to reach a conclusion. In addition to the site specific problem, this method could also be used to develop a large inventory of known problems and reduce the work necessary to catalogue images by having the computer automatically characterize and classify the image. This procedure would involve image processing to obtain a "signature" of the cracking pattern.

7.2.2 Knowledge Base Storage

Inherent with image processing for condition assessment is the need to maintain large quantities of images. The largest magnetic disk capacity available on microcomputers today is nearly 300 megabytes. This will not be adequate for future archival needs for expert systems. Giga bytes of storage will be needed to store the hundreds, even thousands of images to support a complex expert system for condition assessment of structures. These requirements plus the need to represent the images in a database will require storage technologies such as optical disk. As the performance (speed) of these devices improve, it will become feasible to integrate these devices into automated maintenance systems. This technology is being investigated at NIST and is being used in work involving an automated maintenance management system for condition assessment [13].

8. SUMMARY

This paper has described the design and implementation considerations of an expert system tool to aid field inspectors in determining the cause of non-structural failures in concrete. This system will be a valuable tool in automating the acquisition of field information, in presenting a hypothesis on how known failures relate to site specific problems, in preserving the knowledge of experts, and in providing a record of the condition of structures at different ages.

9. ACKNOWLEDGEMENTS

The authors wish to thank the US Army Corps of Engineers, Construction Engineering Research Laboratory, Champaign, Illinois for funding of this research. We also wish to thank Robert E. Philleo, Consultant for serving as domain expert and for critiquing the expert system.

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```
**     CRACKS EXPERT SYSTEM        **
National Institute of Standards and Technology

This knowledge based system is intended to assist
users in assessing the causes of cracks in concrete.

Images of cracks in concrete from known causes are
integrated into the expert system.

This system deals only with non-structural causes
of cracks.
```

TO BEGIN THE SESSION PLEASE PRESS THE 'STRT' FUNCTION KEY (F3)
OR THE 'ENTER' KEY

```
Would you like to see the factors considered in
identifying the causes of cracks in concrete?
```

Yes

---> No

```
What is the age of the concrete when the cracks were first
observed?
```

---> Before Hardening

Don't Know

After Hardening

Figure 1. CRACKS sample session for early concrete.

What do the cracks look like? are they:

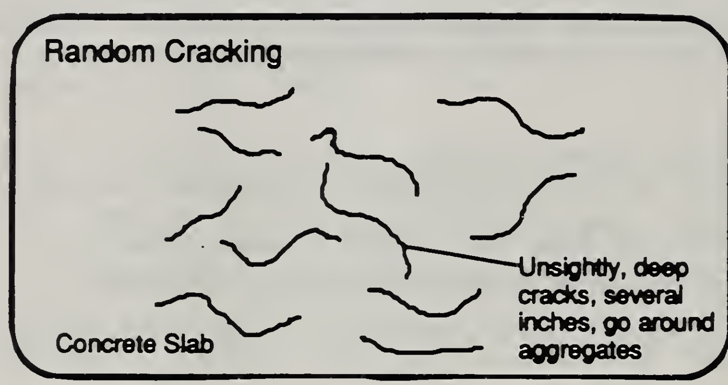
Random

Diagonal

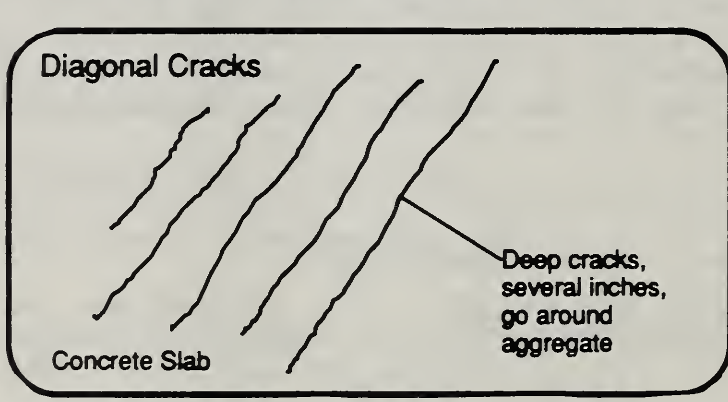
Over reinforcement

In thin walls

---> View crack patterns



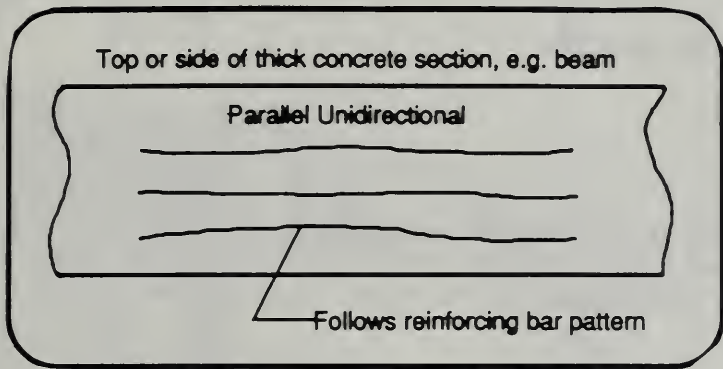
Depress the enter key when
finished viewing image



Depress the enter key when
finished viewing image

Figure 1. CRACKS sample session for early concrete.

Depress the enter key when
finished viewing image



Depress the enter key when
finished viewing image

```
.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.
.                                                                 .
.                                                                 .
.  What do the cracks look like? are they:                        .
.                                                                 .
...................................................................
```

Random

Diagonal

---> Over reinforcement

In thin walls

Figure 1. CRACKS sample session for early concrete.

```
.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.?.
.                                                                .
.                                                                .
.  What type of element is this?                                 .
.                                                                .
..................................................................

                    Thick section

               --->  Slab


**********************************************************************
   The following is a list of all the conclusions CRACKS can make
   concerning the probable causes of pattern cracks in concrete
   for this session:

     *
     * This crack may be a plastic shrinkage crack.  An example
     * of a plastic shrinkage crack is displayed on the image
     * monitor.
```

Figure 1. CRACKS sample session for early concrete.

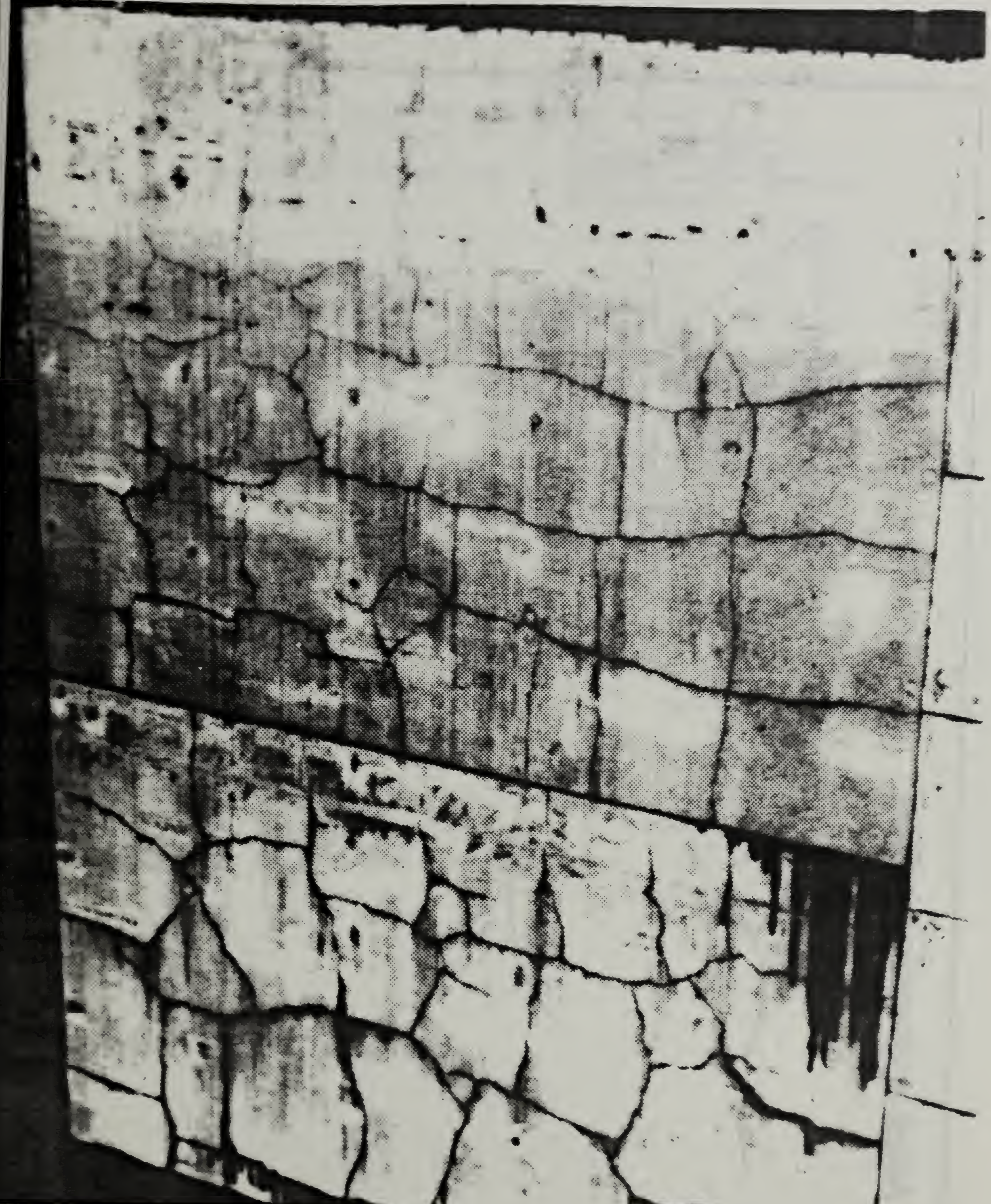


Figure 5. Example of CRACKS photograph

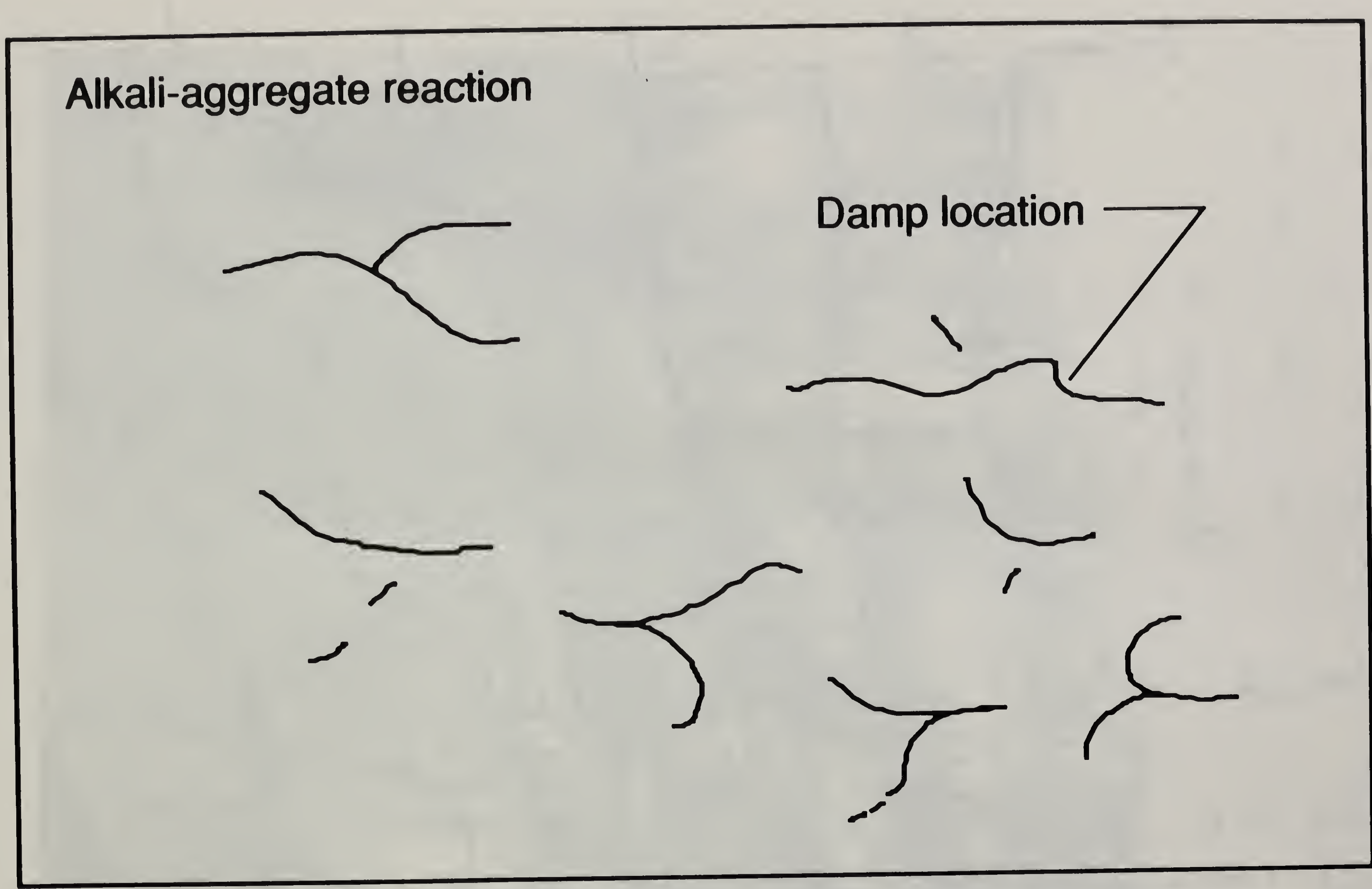


Figure 6. Example of CRACKS drawing

```
•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•
•                                                                 •
•   Do you want to access the utility functions?                  •
•     By selecting "YES" you may: 1. Print conclusions            •
•                                 2. Display chronology           •
•     By selecting  "NO" you may: 1. Conduct another session      •
•                                 2. End sessions                 •
•                                                                 •
•••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••

                   Yes

             --->  No

•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•?•
•                                                                 •
•   Select "Recycle" to do another session or "End Session" to    •
•   quit.                                                         •
•••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••••

                   Recycle session from beginning

             --->  End session

C:>
```

Figure 1. CRACKS sample session for early concrete.

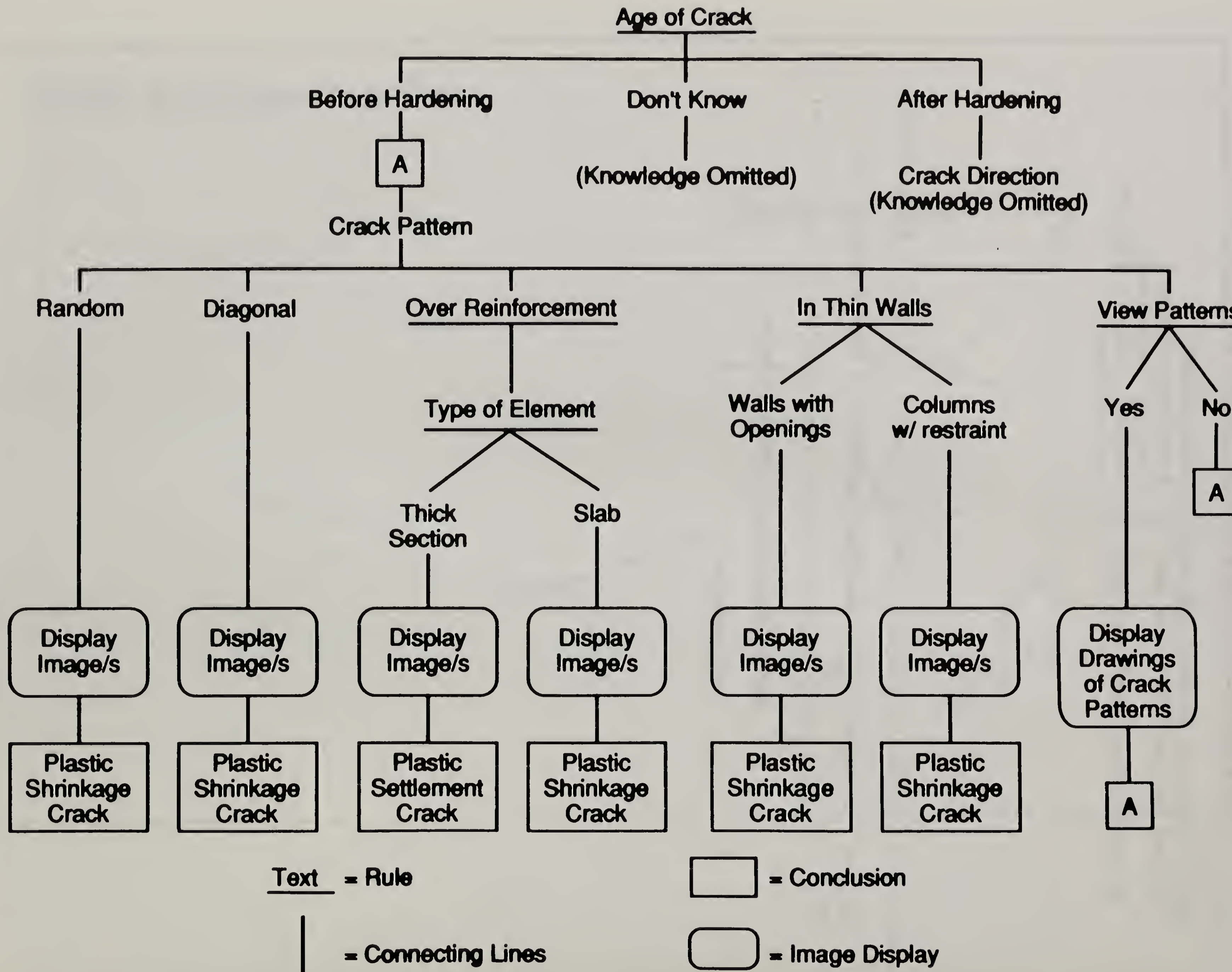


Figure 2. Portion of CRACKS knowledge tree.

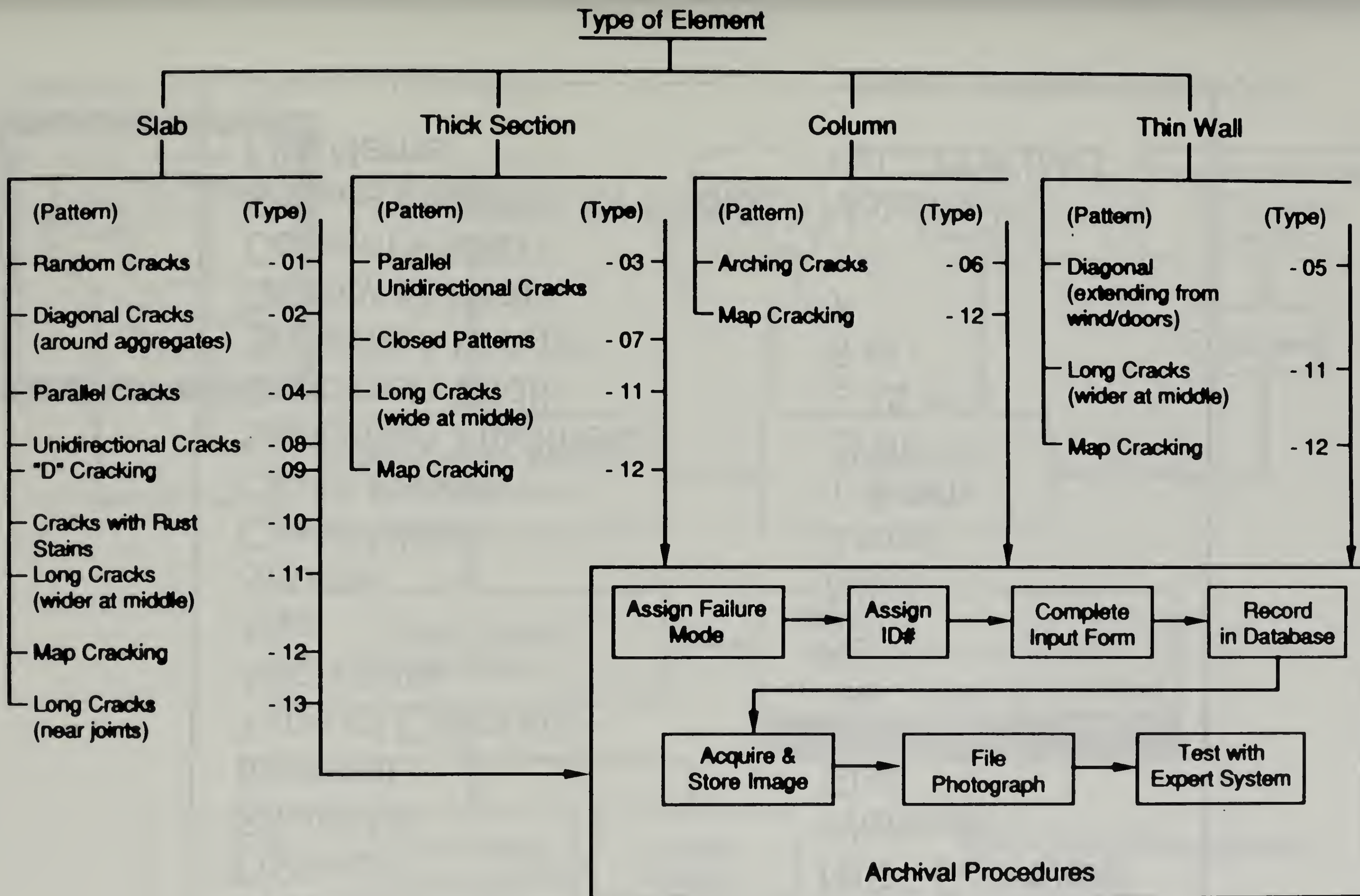


Figure 3. Procedure for describing images.

Field	Example Value
Identification No.	0001
Type Problem	04
Problem Mode	Plastic Shrinkage
Location	NIST Courtyard
Structure	Walkway
Element	Slab
Type of Concrete	I
Aggregate	.75
Age	25
Source	NIST
Crack Width	3 mm
Crack Length	1.6 mm
Specimen Thickness	.3 m
Specimen Width	2.75 m
Specimen Length	5 m
Quality of Photo	7
Color of Photo	1
Source Location for Photo	Volume I
File Name	IMG0004.IMG

Figure 4. CRACKS database schema.

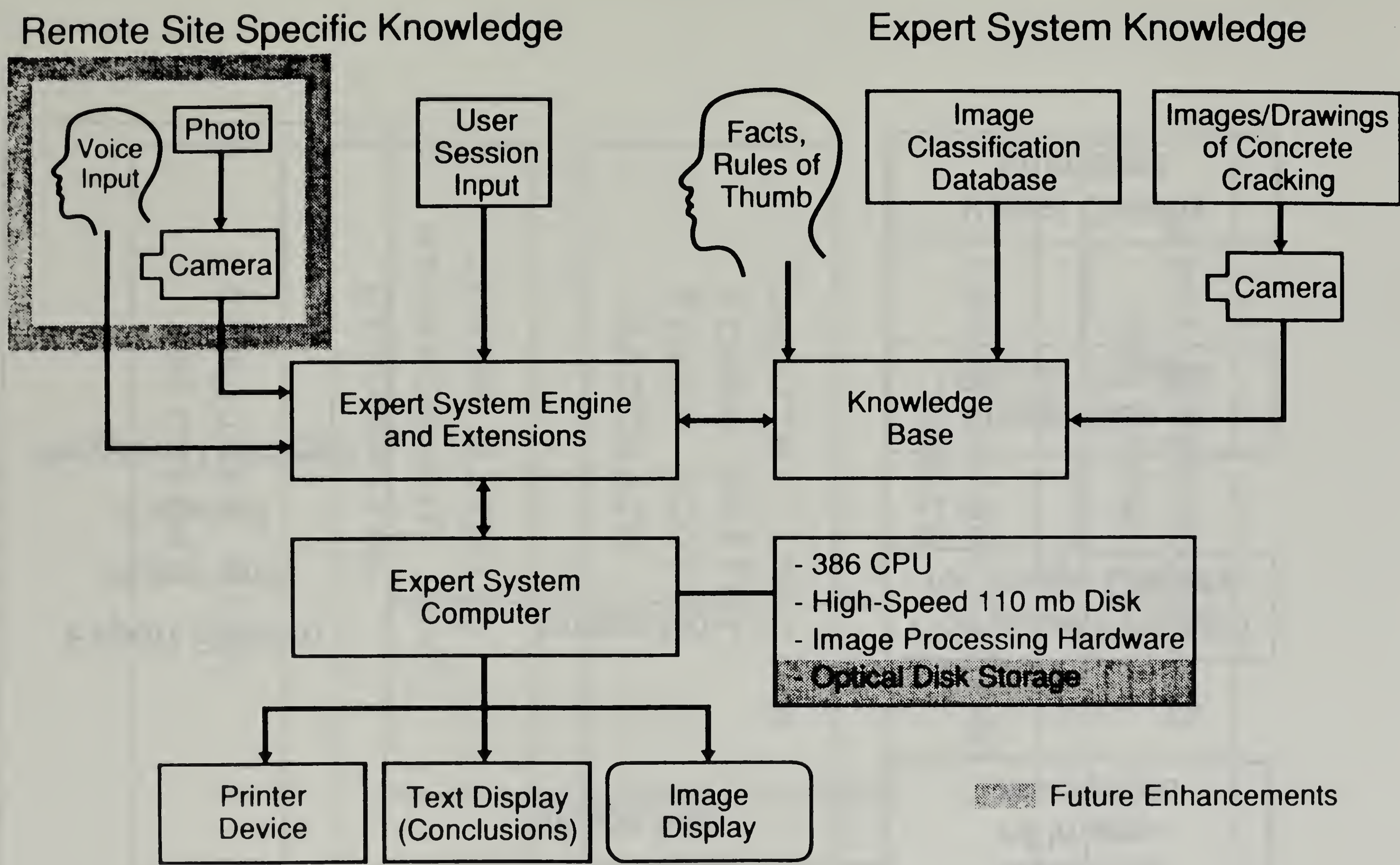


Figure 7. CRACKS expert system configuration.

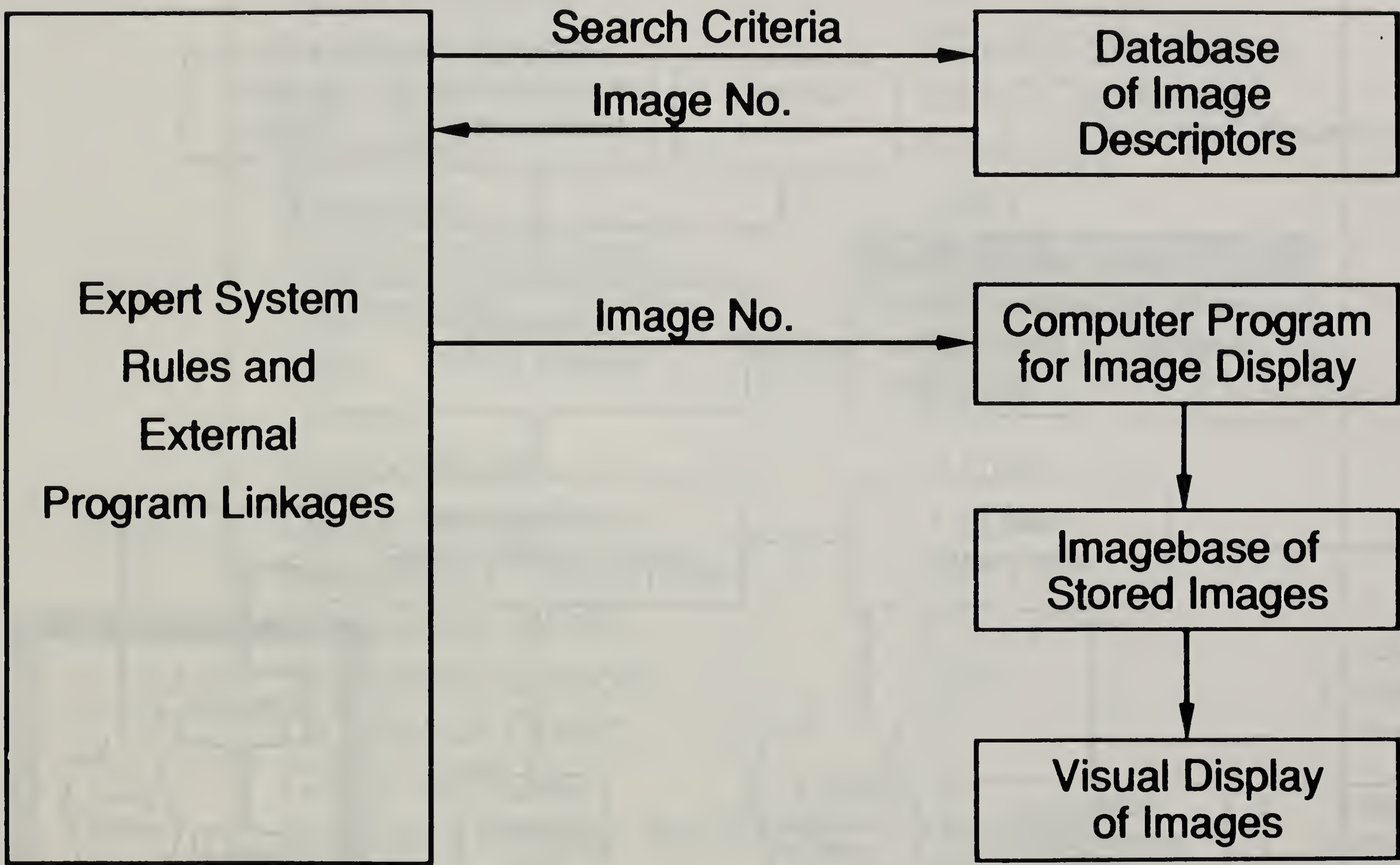


Figure 8. CRACKS expert system knowledge linkages.

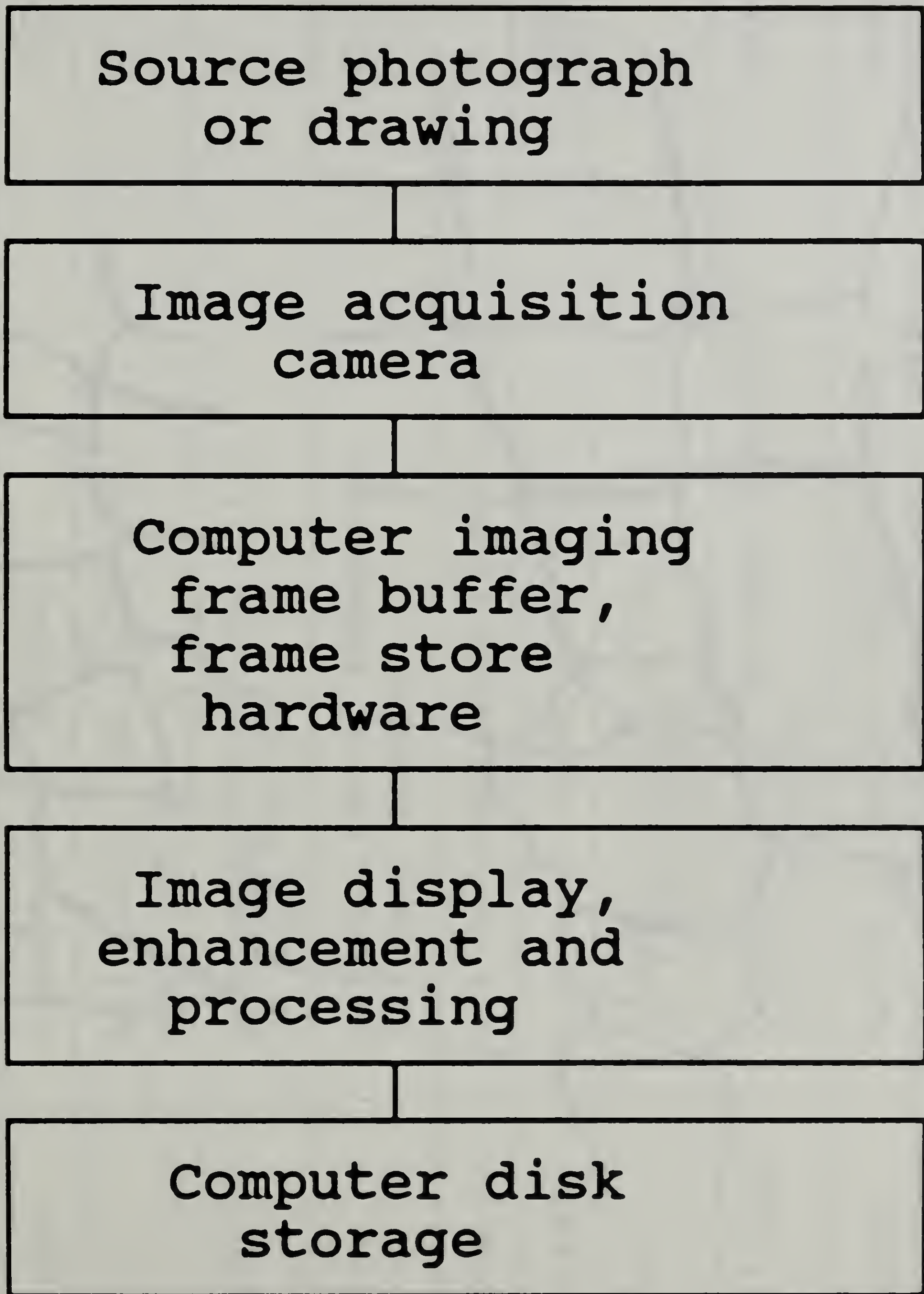


Figure 9. CRACKS image acquisition.

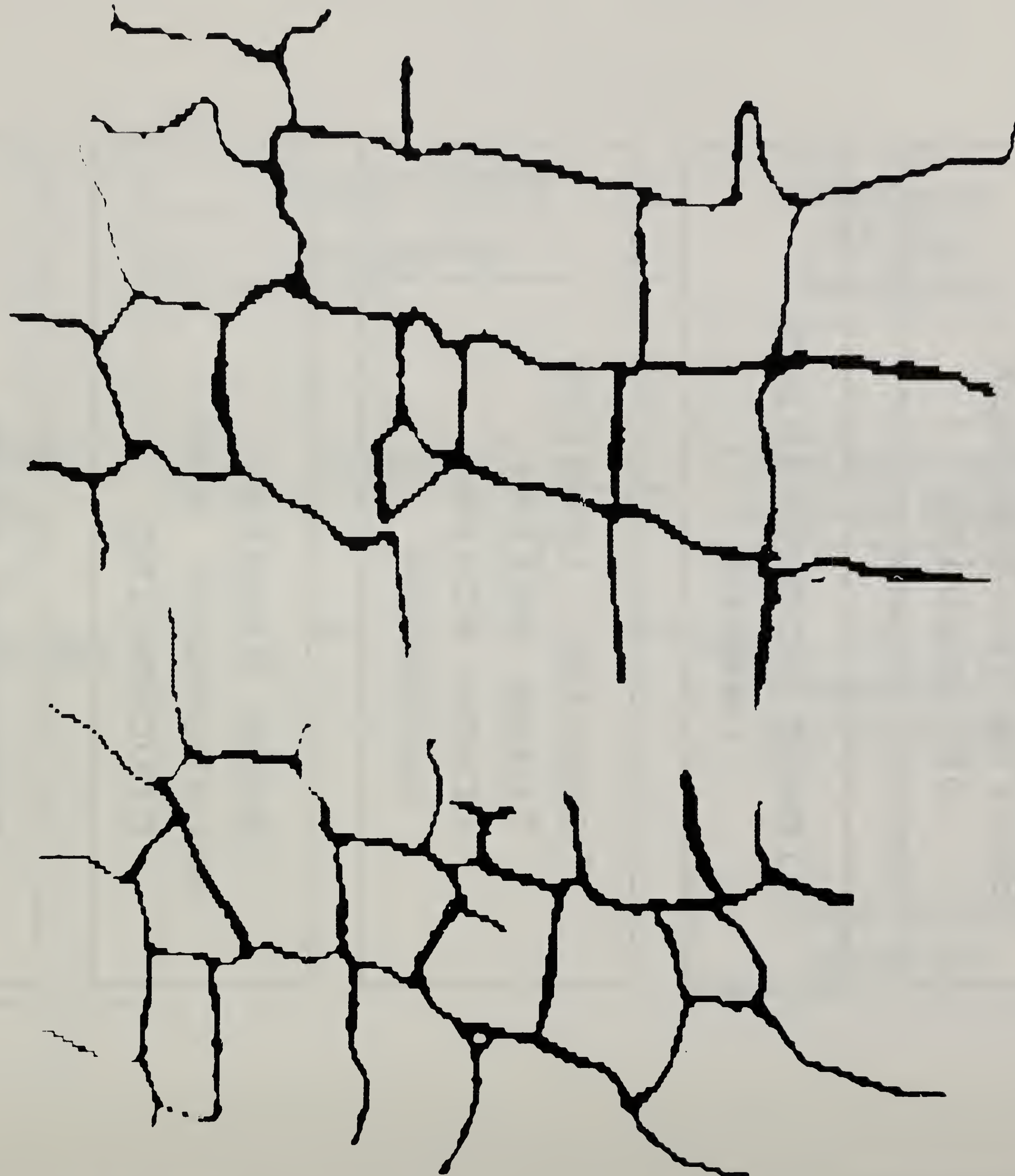


Figure 10. Example of image processing of a concrete crack.

Program	Function	Language
clrim.pas	clears image screen	PASCAL
clrtxt.c	refreshes text files for user session	C
dspchron.c	displays chronology file on text screen	C
prtlof.c	prints line of reasoning for user session	C
prtrecom.c	prints conclusion file	C
rdcrim.pas	reads an image from disk	PASCAL
recomd.c	displays conslusion file on text screen	C
scrwait.pas	causes a wait so that operator can view image	PASCAL
svcim.pas	saves a CRACKS image to disk	PASCAL

Table 1. CRACKS computer program extensions.

Component	Manufacturer [Model]	Description
80386 computer	Compaq Computer Corp. [386/20S]	80386 central processor 4 mega bytes memory 110 mega byte disk hardware disk caching VGA graphics adapter
Image processing frame grabber, frame store hardware	Imaging Technology Corp [PCVision]	8 bit, 512 X 512 pixel resolution, black & white
Video camera	Dage-MTI [Series 68]	black & white
Image display	Sony [PVM-1342Q]	color display

Table 2. Computer hardware capabilities.

Software	Manufacturer [Version]	Function
Disk Operating System (DOS)	Compaq Computer Corp. [3.3]	Contains supervisor calls, device drivers and system utilities
Level 5 PC expert system shell	Information Builders, Inc. [1.3]	Expert system development and infererence procedures
C compiler	Borland International [2.0]	Provides file and screen management facilities via calls from expert system rules
PASCAL compiler	Microsoft Corporation [3.0]	Provides image processing application calls to ITEX/PC sub-programs
ITEX/PC sub-program library	Imaging Technology, Inc. [1985]	Provides image processing functions

Table 3. Computer software capabilities.

Program	Function	Used by CRACKS	Used independent of CRACKS
initialize	Initializes all image processing hardware	X	
sclear	Clears the entire image screen	X	
sethdw	Defines the image processing hardware settings	X	
snap	Acquire and store a single frame (image)	X	X
readim	Read an image from disk	X	
saveim	Save an image to disk		X
histogram	Generate a histogram		X
zoom	Enlarge a portion of an image		X
squish	Condense an entire image into quandrant 0		X
roberts	Perform a roberts edge filter		X

Table 4. Image processing capabilities.

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☐ DOCUMENT DESCRIBES A COMPUTER PROGRAM; SF-185, FIPS SOFTWARE SUMMARY, IS ATTACHED.

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

An expert system has been developed for identifying the probable causes of cracks in concrete based on their shape, and pattern, density and location. The system uses three forms of knowledge: 1) facts, rules of thumb, 2) databases, and 3) digital imaging capabilities. Knowledge contained in the system is obtained from experts in the field, photographs taken of actual concrete failures and the classification of the failures into a database format. A PC based expert system shell and computer programs written specifically for the integration and use of knowledge were used to implement the expert system. This paper discusses the acquisition of the three forms of knowledge, its representation in the expert system environment and extensions developed to process information and enhance the user's interface. The potential for the use of speech recognition for recording conditions of field sites, and storage of large volumes of information using optical disk technology are discussed.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)
concrete cracking; database; diagnostics; expert system; image processing; knowledge acquisition

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